Energy xxx (2016) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

An integrated multi-scale approach to assess the performance of energy systems illustrated with data from the Brazilian oil and natural gas sector

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
3 May 2016
Accepted 9 June 2016
Available online xxx

Keywords:
MuSIASEM
Integrated assessment
Energy system
Oil
Natural gas
Brazil

ABSTRACT

We apply Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to the performance of society's energy system, and illustrate our approach with data from the Brazilian oil and natural gas sector. Key features of MuSIASEM include the multi-scale property and use of grammars. The former builds on a dual definition of the energy system: functional components or (sub)sectors are described as aggregate energy flows (extensive variables) using top-down information from statistics, while structural components (plants, technologies) are described as unitary operations (intensive variables). Integrating descriptions, we can scale information across the energy system's complex hierarchical organization. Use of an energy grammar mandates the pre-analytical definition of accounting categories, primary energy sources and energy carriers; thermal (e.g., fuels) and mechanical energy (e.g., electricity), and a set of expected relations over the different energy forms. Our preliminary analysis shows that MuSIASEM effectively describes the required investment of energy carriers (in quantity and quality) and other production factors, such as labor, in society's energy sector.

1. Introduction

The energy sector is the ‘motor’ that powers all activities of modern society. A comprehensive understanding of its functioning is essential not only for deciding on internal energy policies (investments, subsidies), but also to elaborate more sustainable economic policies [26,47,48]. For this reason and because of the global crisis of the existing pattern of economic growth that cuts across the different dimensions of sustainability – ecological economic and social – it is becoming essential to rethink the way future economies will use energy in order to keep producing and consuming their goods and services [3,7,10,12,18,19,27,28,44]. To achieve these goals it is essential to develop more effective approaches to the integrated assessment of the performance of energy systems [19]. A contribution toward the achievement of new approaches to quantitative energy analysis is presented in this paper. The text of the paper is organized as follows: (i) Part 1 briefly discusses the existence of deep epistemological challenges that have to be addressed to improve the usefulness of the assessment of the performance of energy systems; (ii) Part 2 presents an example of application of an innovative accounting system based on the rationale of MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) to the oil and gas sector of Brazil, that avoids some of the pitfalls of conventional energy accounting; (iii) a short section of conclusions closes the paper indicating shortcomings of this application and the next steps in this line of research.

2. Assessing the performance of energy systems: an overview of epistemological conundrums

2.1. Basic problems with energy accounting

The accounting of quantities of energy (like any other accounting) requires the use of given units of measurement, such as the joule (J), kilocalorie (kcal), or kilowatt-hour (kWh). However, not

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http://dx.doi.org/10.1016/j.energy.2016.06.058
0360-5442/

necessarily energy quantities expressed in a common unit of measurement can be summed. No accountant will sum 100 US$ of profit, to 100 US$ of gross revenues, to 100 US$ of taxes, only because they are measured in the same unit: US$. In the same way, there are different energy forms that even if measurable in (or reducible to) the same unit – e.g. joules – cannot be summed because they are non-equivalent in their qualitative nature [19]. In particular there are two key distinctions that have to be considered when coming to the accounting of quantities of energy: (1) thermal energy vs mechanical energy – the qualitative difference between these two forms of energy is what generated the field of classic thermodynamics – i.e. how to study the conversion of quantities of thermal into mechanical energy and viceversa; and (2) primary energy sources versus (secondary energy) energy carriers. The acknowledgment of a qualitative difference between these two forms of energy is essential to discuss of energy security. In fact, according to the first law of thermodynamics, primary energy sources cannot be made by technical processes. They must be already available in the external world in order to have further energy transformations. When considering these two distinctions, we end up with (at least) four distinct categories that must be used in energy accounting. This is illustrated in Fig. 1 (after [19].

As regards the first distinction between thermal and mechanical energy, the qualitative difference between these two forms of energy was first pointed out by the pioneers of thermodynamics. The operation of a thermal engine clearly shows the difference in quality between 1 J of thermal and mechanical energy, as in this process we 'sacrifice' a larger quantity of J of thermal energy to obtain a smaller quantity of J of mechanical energy. In the same way, when producing Energy Carriers from Primary Energy Sources modern energy sectors sacrifice large quantities of thermal energy (joules in the form of fossil energy) to produce a smaller number of joules of electricity (a form of mechanical energy). It should be noted that also when transforming Energy Carriers into Energy Services this distinction remains essential: converters of energy carriers into useful energy are specific for these two energy forms: big airplane liners are not running on electricity, light bulbs do not run on diesel!

As regards the second distinction – primary energy sources vs (secondary energy) energy carriers – primary energy sources are defined as quantities of referring to forms of energy made available by processes beyond human control – examples are fossil energy, solar energy, and wind energy. Energy carriers (also called 'secondary energy') are forms of energy generated by processes under human control and powered by primary energy sources: e.g. 42 MJ associated with 1 kg of gasoline. This distinction it is important because the production of energy carriers requires: (i) the availability of primary energy sources (e.g. crude oil to be extracted); (ii) the availability of technological power capacity (e.g. technology needed to extract, transport and convert crude oil into fuels); (iii) the availability of human control (e.g. labor); and (iv) the availability of energy carriers to be used to power the activities required for their own production [19]. So the analysis of energy security can be divided in two different aspects [19]:

* when studying the existence of external limits we have to study the conversion of Primary Energy Sources into Energy Carriers. That is we have to analyze the relation between available Primary Energy Sources and available production factors (labor, technology and energy carriers used as inputs) in the energy sector;
* when studying the ability of delivering the expected energy services to the rest of society we have to study the conversion of Energy Carriers into End Uses. That is we have to study the quantity and the mix of production factors (labor, technology and energy inputs) required for achieving an expected set of energy services (the useful tasks associated with socio-economic activities) in the various sectors of the economy.

The need of using at least four distinct categories of energy accounting is in general ignored in the handling of quantitative characterization of energy flows. For example, if we assess the total

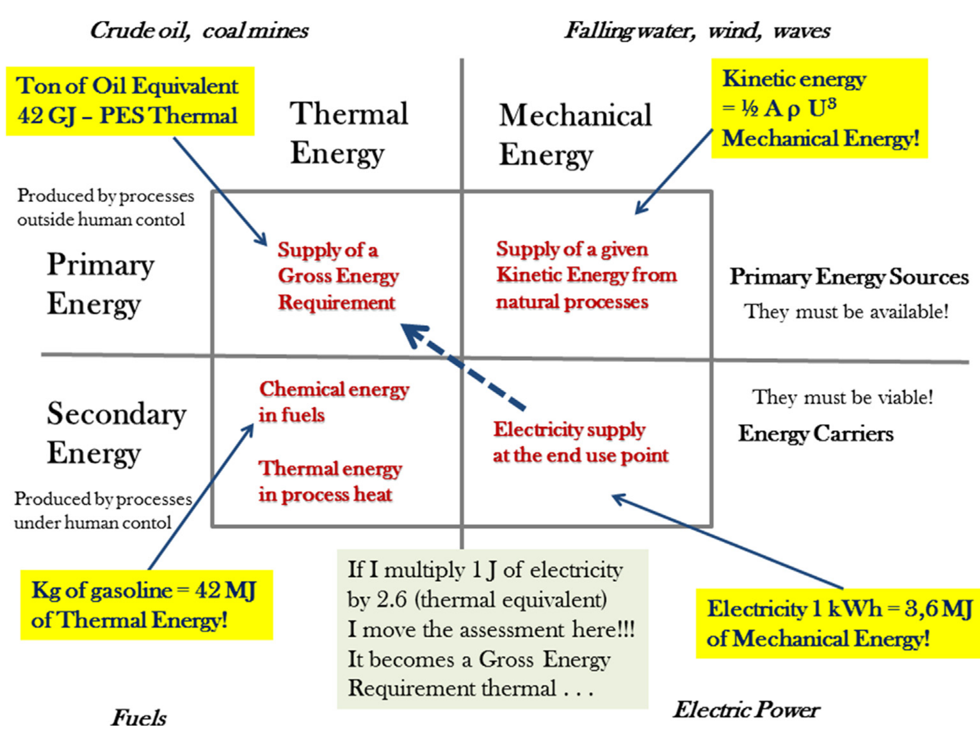

Fig. 1. Example of categories of energy accounting generating non-equivalent assessments.